Nonlinear Time-Dependent Currents in the Surf Zone

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LONG-TERM GOAL

The goals of this work are to develop better understanding and predictive capability for nearshore currents forced by breaking waves in the surf zone.

OBJECTIVES

The major tasks to be accomplished are:

(1) Couple the wave field to the evolving currents in physical-mathematical models for situations that produce alongshore currents and rip currents. As currents evolve the distribution of surface wave breaking adjusts because of the wave refraction caused by the currents. Subsequently the momentum input to the currents is altered. We will examine the influence of feedback from the currents on the wave radiation stress gradients that parameterize momentum forcing from wave breaking.

(2) Examine rip current dynamics for different parameter ranges of wave height, incident wave angle, bottom friction, and beach bathymetry.

(3) Investigate the influence of alongshore-topographic variability (transverse bars) on alongshore currents over plane beaches (i.e., without alongshore-parallel sandbars).

(4) Simulate field conditions at Duck, N.C. using measured beach bathymetry and wave field conditions from the Delilah and Sandy Duck experiments. This “best effort” model will include tides, non-linear bottom friction, and coupled wave-current interactions.

APPROACH

The work involves theoretical development, numerical computations and comparison with field and laboratory results. The primary experimental tools are the depth-integrated and time-average (with respect to the wave period) shallow water equation models including parameterization for the wave forcing effect and bottom friction (Slinn et al., 1998, 2000). Process studies are conducted for different key nearshore parameters (incident wave angle, wave height, bottom friction coefficient, beach bathymetry, etc.) to determine the effects on the flow response.

WORK COMPLETED

We have completed the modification of the numerical model to couple wave refraction with the evolution of currents. This is implemented by time-stepping partial differential equations for the wave numbers and the wave energy together with the non-linear shallow water equations. We have applied this new model to the case of rip currents. While the previous model (not including wave-current interaction) predicts the offshore extent of rips too far to be realistic, the present model shows that this offshore extent can be reduced by half when wave-current interaction is considered. An important factor is the strain of the narrow rip currents that causes work to be done on waves by currents. For the cases when circulations are physically unstable, instabilities seem to start initially at the near shore where rips are ‘fed’ by alongshore currents, rather than at the rip heads far offshore as predicted without wave-current interaction.

RESULTS

The numerical results consistently show that the offshore extent of rip currents is significantly reduced when wave-current interaction is included. This can be seen from Figure 1, showing vorticity fields for rip currents that have developed on a beach with sinusoidal alongshore variations. A shore-parallel sand-bar is located approximately 80 m offshore with transverse bar troughs (rip channels) located at y=0, 256, and 512 m and transverse bar crests at y=128, 384, and 640 m. Without the wave-current interaction, cf. Figure 1(a), the circulation can extend approximately 600 meters from the shoreline even with moderate bottom friction parameterization and very shallow rip channels (30 cm deep). This seems to be too far to be realistic, based on experience with field observations for moderate wave field conditions (e.g., Smith and Largier, 1995). Upon including wave-current interaction, however, the circulation is confined within approximately 200 meters of the shoreline, cf. Figure 1(b). The physical explanation is discussed below.

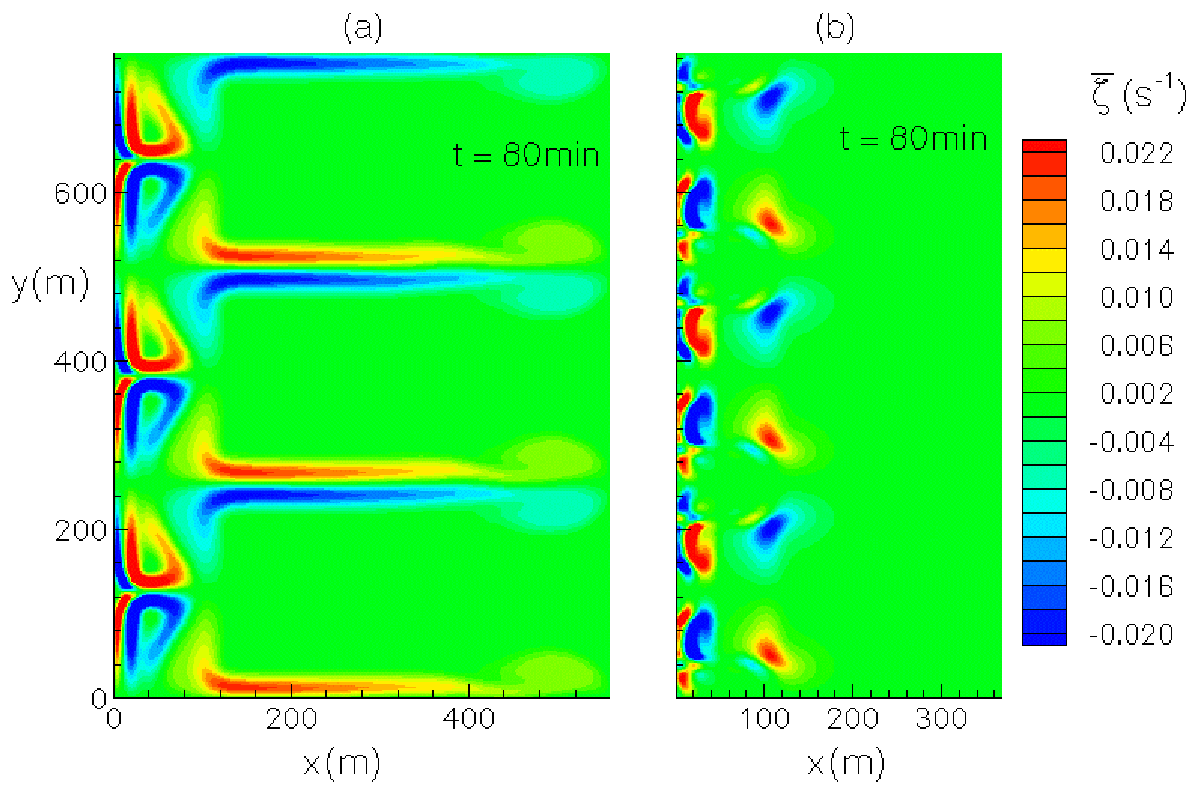

Figure 1. Instantaneous vorticity fields for normally incident waves with offshore wave height 1 m, bottom friction μ=0.002 m/s, (a) without wave-current interaction, (b) with wave-current interaction.

In the present study, it is the deviation of the wave forcing from its alongshore mean that causes the circulation. Before currents develop, this deviation is mainly set up by the alongshore variation of the topography through wave refraction. At a transverse bar crest, breaking is enhanced because of the reduction of the water depth, and more wave momentum is expected to be transferred into currents; at a rip channel, the opposite is true because of the greater water depth. This effect is enhanced by wave ray focusing towards the local bar crests. As a result, the deviation of the x-forcing from its alongshore mean at a rip channel is negative (since the mean is negative), cf. Figure 2(a), and forces a seaward directed flow (rip current), while it is positive at a bar crest and forces an onshore flow. If such a forcing persists, *i.e.*, without considering the effect of currents on waves, rips will grow stronger as time progresses and advect vortices offshore at rip channels. In the offshore region, there is little bottom friction and practically no wave forcing of mean currents. Thus, vortices can reach to a great distance. The wave field, however, is changed because of the wave refraction due to the currents, cf. Figure 2(b). Note that at t=20 min the positive x-forcing at rip channels is reduced in strength and becomes negative at some locations. The reason is that the strain of the offshore directed rips causes work to be done on the waves by the currents. This results in an increase of the wave energy offshore at rip channels, cf. Figure 2(c) x=100 m – 200 m, and leads to stronger breaking as waves propagate further onshore. This effect of wave refraction due to currents is opposite to that due to the topography at a rip channel, and hence, compensates for the effect of wave forcing produced by the topography. In summary, as rip currents become strong and narrow, they produce a negative feedback on the wave forcing, which tends to reduce the strength of the currents.

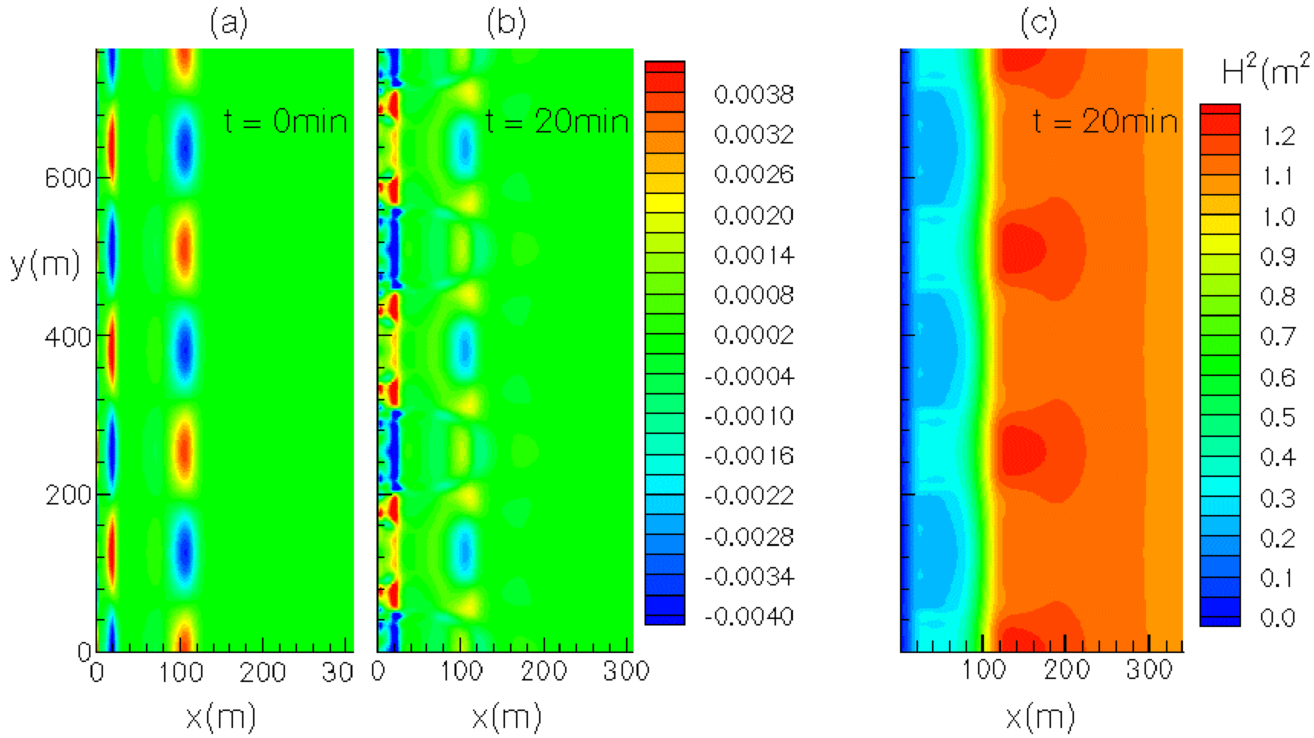

Figure 2. The deviation of the x-forcing from its alongshore mean (a) before currents develop; (b) after rip currents are present; and (c) the wave energy density in the presence of rip currents. The physical parameters are the same as in Figure 1.

In the cases when circulations are physically unstable, the simulations show that instabilities develop initially at the near shore where rips are 'fed' by alongshore currents, rather than at the rip heads far offshore as previously predicted without wave-current interaction. There are two kinds of unstable flows: (i) the velocities of the circulation oscillate in time in a more or less regular manner, cf. Figure 3(a)-(d), (ii) the velocities fluctuate irregularly, being accompanied by vortex shedding from the currents, cf. Figure 3(e)-(f).

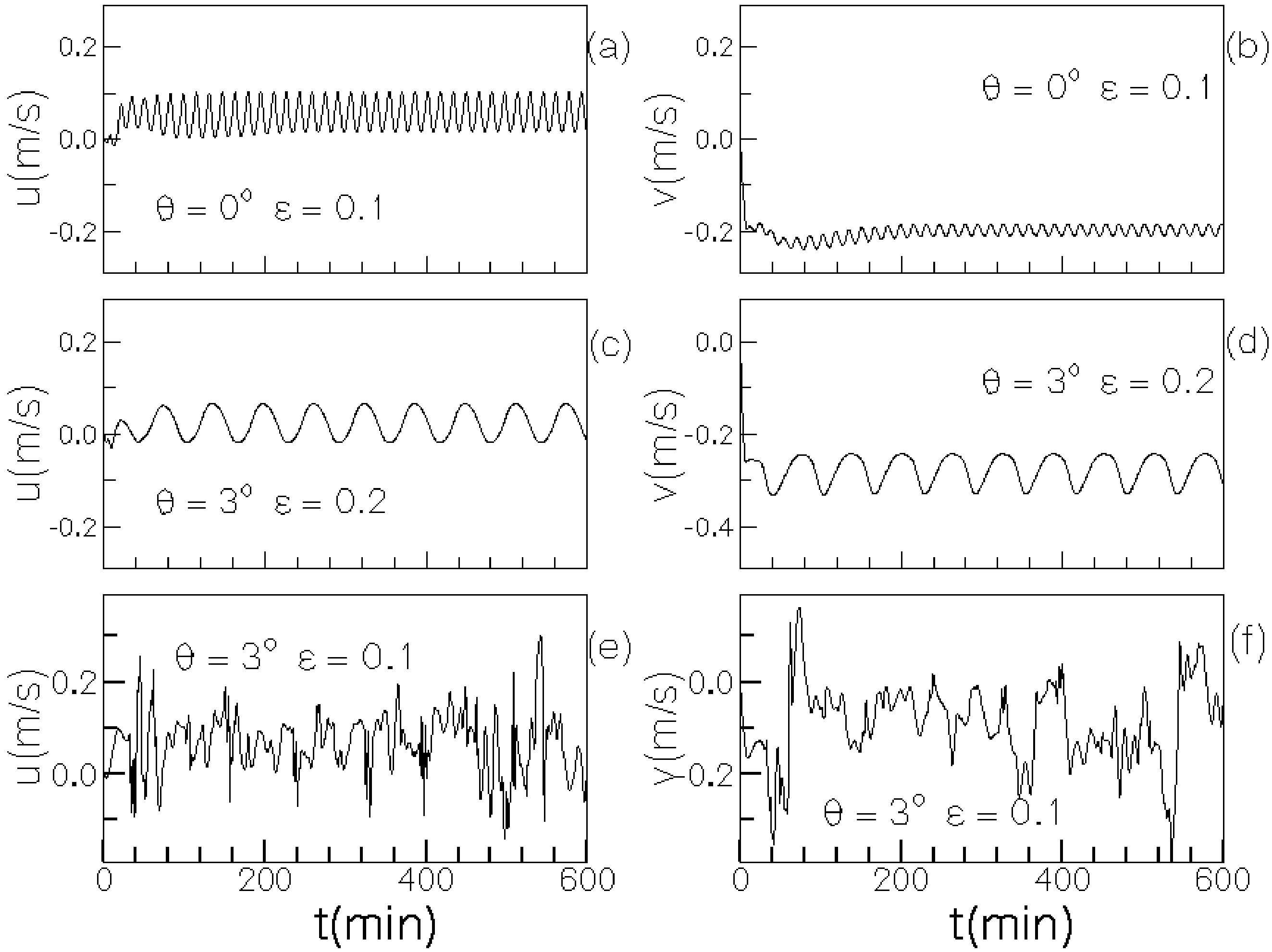

Figure 3. Time series of the across-shore and alongshore velocities (u,v) at x=81 m, y=320 m, θ is the wave incident angle in deep water, ε is the nondimensional amplitude of the alongshore variation of the bottom topography; (a)-(b) wave height 0.8 m, bottom friction 0.0025 m/s; (c)-(d) wave height 1.0 m, bottom friction 0.003 m/s; (e)-(f) wave height 1.0 m, bottom friction 0.0015 m/s.

Our experiments also show that when waves are not perfectly normally incident the circulation becomes more unstable. This, together with the observation that instabilities initiate in the region where rips are 'fed' by alongshore currents, seems to suggest that the alongshore component of the circulation is a controlling factor of the instability. These issues are under investigation.

IMPACT/APPLICATION

Improved understanding of the near shore environment has potential benefits for society in several areas. These include shore protection against beach erosion, understanding the behavior of shoaling waves, keeping waterways open for shipping in harbors, ports and inlets, safety for recreational beach users (e.g., from dangerous rip currents) and in defense of the nation when activities encompass littoral regions. We will have a strong indication that we understand and can quantify important nearshore processes when predictive models can match field observations. For the scientific community, this is still a work in progress.

TRANSITIONS

Our two major transitions have been (1) determination and implementation of the most appropriate wave-current interaction model and (2) changing focus from alongshore current dynamics to rip current dominated situations. The project was joined in November 1999 by Dr. Jie Yu as a Post-Doctoral Research Associate (PhD, MIT, Civil Engineering, 1999).

RELATED PROJECTS

1. Tuba Ozkan Haller at the University of Michigan is investigating coupling of mean currents and radiation stresses, using a formulation different from our approach, focusing primarily on longshore current behavior, that should be valuable to confirm flow features with similar behavior.

2. A group of near shore researchers, led by Jim Kirby at the University of Delaware, are developing near shore community models. We expect to benefit from and contribute our ideas to their modeling studies.

3. The Sandy Duck 1997 field experiments, led by Bob Guza at Scripps Institution of Oceanography, collected valuable information for calibration and testing of our models. Of particular interest are field observations of mean currents by Jerry Smith.

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PUBLICATIONS

Slinn, D. N., J. S. Allen and R. A. Holman 2000: Alongshore currents over variable beach topography, J. Geophysical Res., 105, 16,971-16,998.